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GREAT PROSPECTS FOR FIBER OPTICS SENSORS

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GREAT PROSPECTS FOR FIBER OPTIC SENSORS

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Fiber optic sensors provide noise immunity and galvanic insulation at the measurement point. Interest in such sensors is increasing for these reasons. In the United States sales are expected to increase from 12 million dollars in 1981 to 180 million in 1991. Interferometric sensors based on single-modus fibers deliver extremely high sensitivity, while sensors based on multimodus fibers are more easily manufactured. The fiber optic sensors which are available today are based on point measurements. Development of fiber optic sensors in Norway is being carried out at the Central Institute and has resulted in the development of medical manometers which are now undergoing clinical testing. /17*

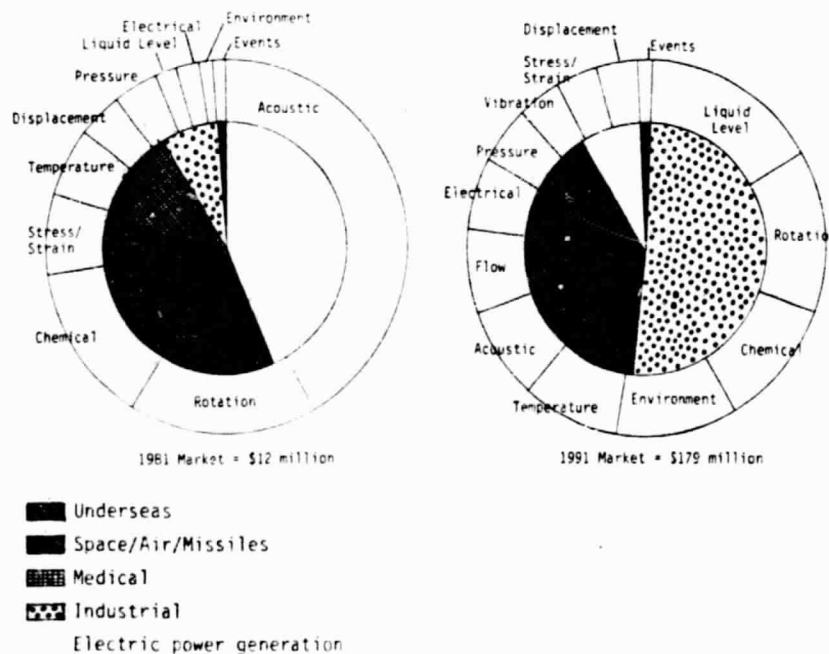


Figure 1. Development of fiber optic sensor market.

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Communication applications usually come to mind when fiber optics is considered. However, in the last few years interest in applying the advantages afforded by fiber optic signal transmission to the construction of various types of sensors has increased. The fact that fiber optics provides immunity from electromagnetic noise and galvanic insulation at the measurement point makes this idea more attractive. Fiber optic sensors can solve measuring problems in situations where conventional sensors with electric connections are not practical. Situations in which strong electromagnetic noise is encountered are found onboard ships and airplanes and in the electrochemical processing industry. Fiber optic sensors can be used to measure high-voltage potentials in high-voltage installations, and galvanic insulation allows measurements in situations where there is danger of fire and explosion. The use of fiber optics eliminates the dangers of patient exposure to dangerous voltages in medical applications.

Strong Increase in the Market

A study carried out by Kessler Marketing Intelligence indicates that the market in the United States is expected to increase from 12 million dollars in 1981 to almost 180 million in 1991 [1]. Development in the fiber optics field has been dominated by military research and development programs for more than five years. For example, the United States Navy has its FOSS (Fiber Optic Sensor System) program, which includes undersea acoustic detection systems, sensors for magnetic fields and fiber optic gyros. Other military programs pertain to guidance systems for planes and missiles.

A not inconsiderable portion of the market in fiber optic sensors is related to civilian applications. Such applications include medical instruments and systems, control systems for electrical power suppliers and industrial processes. In terms of dollars it is expected that these applications will soon exceed the military activities. As of 1991 it is expected that the industrial applications will be dominant.

Fiber optic sensors for temperature, vibration, rate of revolution (tachometers), fluid level and two-phase current measurements are commercially available at the present time. In addition the literature contains descriptions of a number of different fiber optic sensors which are in the developmental stage, but not all of these have been realized experimentally.

Interferometric Sensors Yield Extremely High Sensitivity

Extremely small variations in the mechanical properties of an optic fiber can result in considerable variation in the optic wavelength of the light which propagates through the fiber. This is evident when we /18 consider that 1 cm of an optic fiber typically contains 10^5 radians of the optical carrier wave. A phase detector with a sensitivity of 1 radian therefore makes it possible to detect a variation of 1 part in 10^5 for 1 cm of optic fiber. The sensitivity increases with the length of the optic fiber, so that 1 part in 10^9 should be easily detectable. If we increase the sensitivity of the phase detector to, for example, 10^{-4} radians then the sensitivity for the fiber optic sensor would be 1 part in 10^{13} .

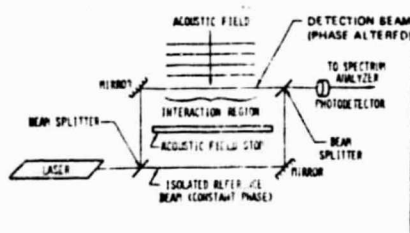


Figure 2. Interferometric Hydrophone. Light from a laser is split between the signal fiber and reference fibers. The light at the output of the two fibers is combined in a photodetector and emits a signal corresponding to the acoustic frequency.

Phase shifts in the optic fiber can be introduced by a number of external influences. This is especially true with regard to stress, pressure and temperature. The most delicate sensor configuration occurs when two "single modus" fibers are used as branches in a "Mach-Zender interferometer". A hydrophone can be based on this principle [2]. In this case the signal fiber is a coil of "single modus" fiber which is exposed to the acoustic field. The resulting variations in the optical wavelength are detected by mixing the light from the output of the sig-

nal fiber with light from a stable reference fiber. An interaction length of 25 cm gives a sensitivity of -135 dB relative to $1 \mu\text{Pa}$ [2] normalized to a bandwidth of 1 Hz. With an interaction length of 10 m and a power level of 10 mW the predicted sensitivity is -180 dB. These data are many orders of magnitude better than those provided by conventional hydrophones.

A considerable effort has been carried out under the auspices of the United States Navy's FOSS program to develop this type of fiber optic hydrophone. Magnetic sensors based on this principle have been realized. One might also mention a microscope for use in acoustooptic spectroscopy and a sensor for measuring movement in the earth's crust. However, the latter have not been realized experimentally.

The design of the "Mach-Zender" interferometer is simple in principle, but the alinement of the optical components is extremely critical. The fundamental problem with interferometric sensors which operate at relatively low frequencies is that the configuration is intrinsically sensitive to vibrations and temperature variations which mask the signal which one wishes to measure. For example the phase response for a temperature change of 1°C is more than 10^6 times greater than the response for a pressure change of 1 Pa [3]! One method of counteracting this effect is to place the signal fiber and the reference fiber in the closest possible physical contact, but no complete solution to the problem has yet been devised. During a study trip to the United States in 1981 the author received the impression that many researchers doubted whether a practical interferometric sensor could be developed at all. One possible exception might be temperature sensors, such as those used to test jet engines, but in this case simpler methods are also available.

Sensors Based on Multi Modus Fibers

A great deal of interest has been expressed in sensors based on multi modus fibers because of the fundamental problems connected with interferometric sensors. In this case the so-called "microbending"

effect, which has been a problem in other applications and caused extra loss in optic fibers used for communications purposes, is used. The principle involved is that deformations or inhomogeneities in the fiber geometry create connections and energy transmissions between various propagation modi in the fiber. For example propagation modi can be connected to modi which stream out from the fiber. The resulting energy transfer represents a damping of the light which is transmitted through the fiber. The effect is dependent upon the difference in the refractive index between the fiber's core and the insulation, and this parameter can be rendered much less temperature dependent than the refractive index for the core alone. However, the sensitivity of this type of fiber optic sensor is lower than that of interferometric sensors.

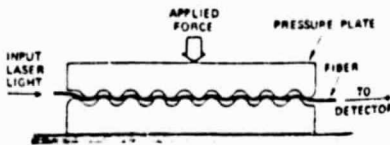


Figure 3. Principle of Microbending Sensor. Two corrugated plates provide periodic deformation of the fiber geometry.

If a fiber is exposed to periodic geometry deformation by squeezing it between two corrugated plates [3] extremely effective coupling is achieved between modi where the difference in number of waves corresponds to the periodicity determined by the corrugations. An indication of the forces which are pressing the plates against one another can be obtained by measuring variations in the optic signal by means of a photodetector. Hydrophones which have equal or better sensitivity than conventional units have been made in this way.

Instead of using corrugated plates it is possible simply to allow the effect which one wishes to measure, such as an acoustic field to work directly on the fiber. This yields an extremely simple sensor configuration. The detection principle is based upon the phase difference between different modi which is caused by the external influence in

question. Sensors for acoustic fields, currents and electrical currents /23 have been designed in this manner. These types of sensors are roughly three times less sensitive than corresponding interferometric sensors, but they are still sufficiently sensitive for many applications.

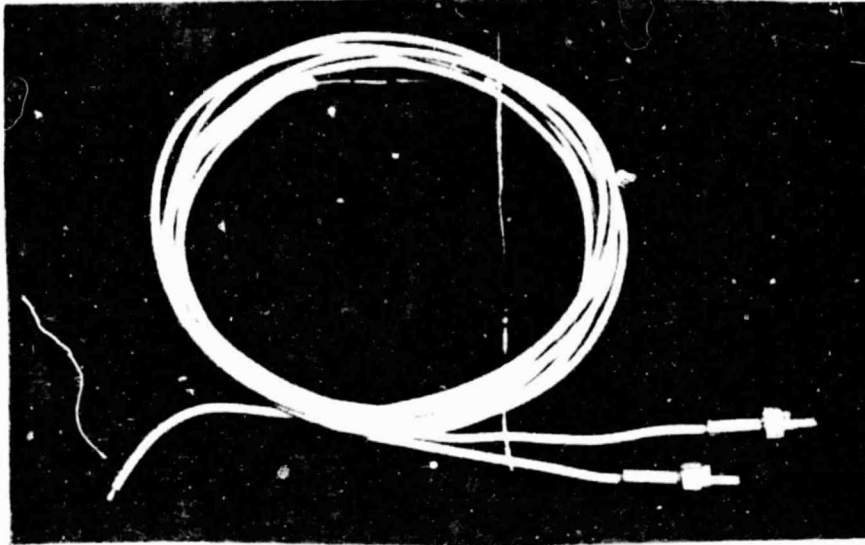


Figure 4. Fiber optic pressure transducer developed by the Central Institute. The greatest diameter is roughly 2 mm, length 2 m. The measurement range extends from -50 to 300 Hg. The sensitivity is better than 0.05 mm Hg. Potential frequency response up to 15 kHz.

Miniaturized Sensors for Point Measurements

The sensors which have been discussed up to this point use the optic fiber itself as the sensitive element. However, a number of sensors have been designed where the optic fibers are used only to conduct light to and from the point of measurement. Here the light path is broken, and the connection between the fibers which lead from the light source and the fibers which lead to the photodetector is modulated by the force to be measured. This provides possibilities for miniaturizing in many cases.

A number of configurations have been realized, and some of these have resulted in commercial products. For example there are temperature measuring systems wherein optic fibers conduct light to and from the measuring tip, which contains liquid crystals which change color

with temperature variations. Thermometers have been marketed where an optic fiber conducts heat radiation from the measurement point to an IR detector. Fiber optic systems for level measurements are constructed by coupling light between two fibers using a prism. The connections will depend upon whether the prism is in the fluid or in the air. Level measuring systems of this type have been installed in atomic reactors, using metal-clad fibers which can tolerate up to 500° C. An entirely analogous principle is employed for measurements in two-phase current. With regard to commercially available fiber optic sensors we should also mention tachometers where an optic fiber bundle is used to measure how rapidly black and white fields on the rotating axle pass by the measurement point. Sensors which use fiber bundles to measure level and vibrations are also available.

Medical Manometers with Great User Potential

The development of fiber optic sensors in Norway has been carried out by the Central Institute for Industrial Research (SI). This work has already been described in Elektro [4]. This development has resulted in medical manometers. The use of fiber optics means that it is no longer necessary to connect electrical wires to the patient. This is important for the safety of the patient, and satisfies the great demands for galvanic insulation imposed by the medical equipment which is now coming into use. The frequency response is excellent because of the miniaturized membrane, which is 1.5 mm in diameter. These manometers are now undergoing clinical testing. Up until now they have been used in the heart/blood vessel system, in the duodenum and in the bladder. In the near future they will be used for measurements in the womb during childbirth. Fiber optic sensors are also used to measure oxygen saturation in the blood. This unit will be combined with the fiber optic manometer in a combination medical probe.

The principle involved in the medical manometers is that the connection between the fibers which lead to the measurement point from the light source and the fibers which lead to the photodetector from the measuring point is modulated by the curvature of the membrane. In future

developmental work at the Central Institute we will attempt to use the fiber itself as the sensitive element. We hope to make use of the microbending effect described earlier. The goal here is to develop sensors for process monitoring in, for example, situations where strong electromagnetic noise is a problem.

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